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IMAGING SHOCKED SAPPHIRE AT 200 – 460 KBAR: THE EFFECT OF CRYSTAL ORIENTATION ON OPTICAL EMISSION

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Abstract. We have taken 12 – 50 ns exposure duration images of 200 – 460 kbar shock loaded, single crystal sapphire (_-Al_2O_3) windows of the c-cut (0001), r-cut (1,-1,0,2) and a-cut (1,1,-2,0) orientations. We find that the spectra of the emission are broad and relatively featureless, extending at least from 760 to 280 nm. Images of this emission at the lower end of the stress range (200 – 220 kbar) show that it is spatially very heterogeneous, coming from a few seemingly-randomly distributed locations within the crystal. This emission heterogeneity becomes more fine-grained with increasing shock stress. Finally, the r-cut orientation produces significantly less emission than the other two orientations at the same stress.

INTRODUCTION

Optical studies of shock compressed materials frequently require the use of an optical "window". Two desirable characteristics of a window are that it be relatively dense and incompressible (so that large pressures can be attained at the sample-window interface) and that it be transparent to optical radiation. Sapphire ought to be a good window material, having a very high shock impedance and excellent transparency at room temperature and pressure. However, the transparency is known to degrade under shock load conditions. Barker and Hollenbach [1] showed that sapphire is unsuitable as a VISAR window above its Hugoniot elastic limit (HEL) near 150 kbar. Webb [2] showed that the extinction of 300 – 500 nm light through c-cut sapphire turned on at the elastic limit and then dramatically increased with stress beyond this. Kondo showed that sapphire emission between 156 and 847 kbar was characteristic of a gray body at approximately constant temperature of 4930 K with emissivity increasing with stress [3]. This measured temperature is well above the 310 to 620 K calculated average temperature for sapphire under Kondo's conditions [4].

Emission is an important aspect of high pressure optical studies. It has a bearing on the correct interpretation of absorption and scattering measurements and optical pyrometry. Earlier emission work in sapphire has been focused on the spectrum of the emitted light [3]. On the other hand, imaging of the emission has been shown to provide useful insight into the deformation mechanisms in other "transparent" crystals such as quartz and lithium niobate [5,6].

In this work we have measured both the spectrum and spatial morphology of shock-induced optical emission from fully oriented pure synthetic single-crystal sapphire for three common crystal orientations and spanning a longitudinal stress range of from 200 to 460 kbar.

EXPERIMENTAL PROCEDURE

The samples were single-crystal synthetic sapphire windows 15.0 mm diameter by 3.0 mm thick and of typical purity better than 99.99%. Window surface orientations were of the (0001) c-cut, (1,-1,0,2) r-cut, and (1,1,-2,0) a-cut . We fully oriented the samples (i.e. identified all crystal axis directions) primarily by using back reflection Laue although optical orientation was used for some of the r-cut specimens.

Figure 1 shows a schematic of the experimental set-up. The samples were coated with 500 nm of chromium and backed by baseplates of either iron or 304 stainless steel (304 SS). A heat-shrink-fitted ring of 304 SS was fitted around the diameter of the sapphire to minimize lateral unloading in the sapphire during the experiment. Shock loading was achieved using a two-stage light gas gun at Lawrence Livermore National Laboratory. This gun is equipped with a gas breech accessory attachment for low projectile velocities. The tantalum flyer plate thickness and velocity range was such that the sapphire behind the shock front was fully loaded during the exposure period. Three electrical shorting pins imbedded in the SS ring triggered the data acquisition equipment.

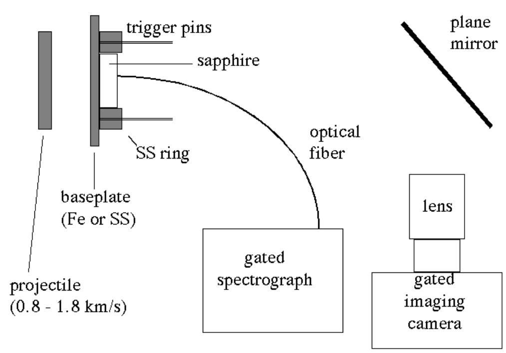

Figure 1. A typical experimental set-up.

The emission spectra were acquired using a monochrometer and gated diode array. The monochrometer was interfaced to the sample via a single 200 micron core UV-enhanced fused silica optical fiber which was resting directly against the sample. A single spectrum was generated per experiment. The exposure duration varied, but was typically between 100 and 150 ns (elastic precursor transit time across sample is about 260 ns, shock transit time is greater still) with the exposure window centered in the transit window.

The gated imaging was performed by a thermoelectrically cooled 576 by 384 pixel intensified CCD taking a head-on view of the rear sample surface. One image was generated per experiment. Exposure time varied from 12 to 50 ns and the exposure window was centered where the shock had propagated about 40 % of the sample's thickness. The camera was operated without bandpass filters and is sensitive to emission throughout the visible spectrum.

RESULTS

The emission spectra of shocked sapphire are broad, extending at least across the full range of our spectrograph configuration (730 nm to 280 nm) and relatively featureless (There is just a hint of a 70 nm wide feature centered at 750 nm). An example is shown in fig. 2. To increase the signal, we used a relatively wide bandpass (15 nm). Although we do not find strong evidence of structure in the emission spectra we cannot rule out the possibility that there is spectral structure on a scale which is much finer than our spectral bandpass.

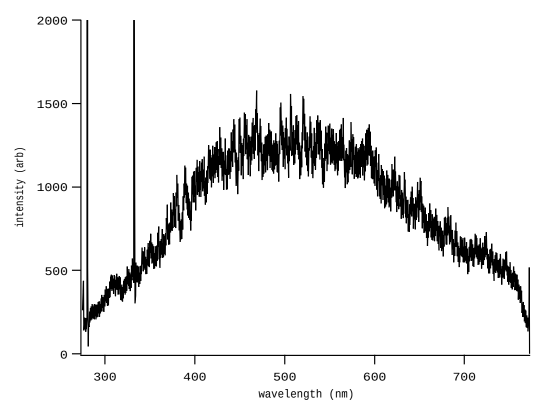

Figure 2. A typical emission spectrum: c-cut sapphire at 460 kbar. Minimum feature width is 15 nanometers. The spikes at 280 nm and 332 nm are artifacts.

The spatial structure of the emission images is very heterogeneous for the a-cut and c-cut orientations at the 210 kbar level. This heterogeneity persists at the 430 kbar range, although the heterogeneity has become much finer grained. Figure 3 illustrates this graininess and its dependence on stress.

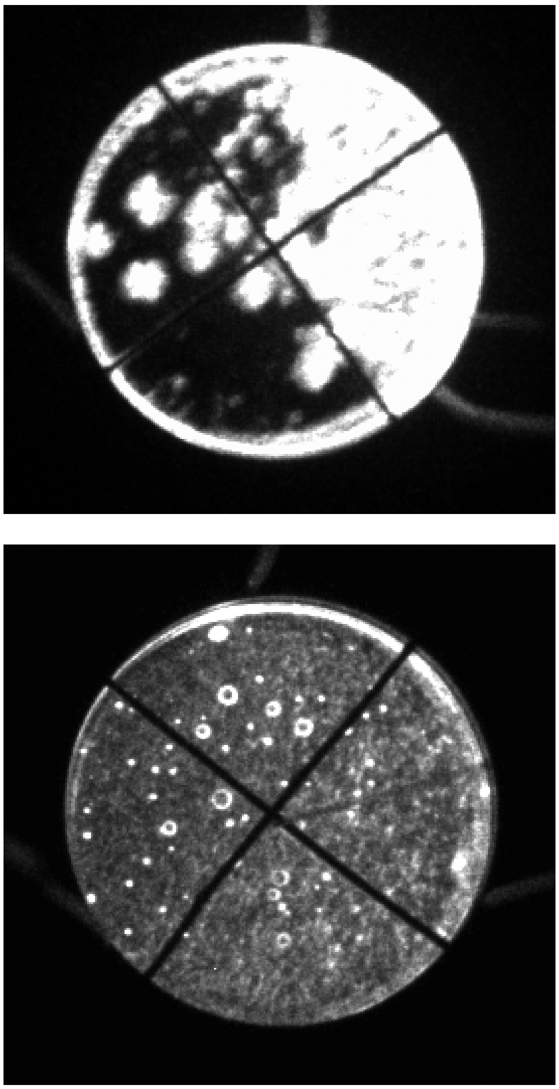

Figure 3. Top: a-cut sapphire loaded to 217 kbar. Bottom: a-cut loaded to 445 kbar. Intensity has been adjusted to bring out the features of the two images. The black cross in the center of each photo is of wire and for alignment purposes only.

In terms of quantitative intensity, the r-cut orientation always showed significantly less emission than the other two orientations under similar stress conditions. Figure 4 illustrates this for the higher stress range of this work. Regarding the shots of fig. 4, the r-cut and a-cut showed 24% and 70%, respectively, of the c-cut optical emission quantity.

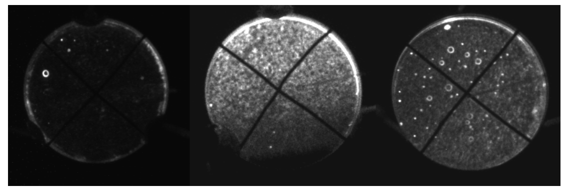

Figure 4. Quantitative comparison of emission intensity from sapphire. Left: r-cut 472 kbar. Center: c-cut 402 kbar Right: a-cut 445 kbar.

DISCUSSION

This work demonstrates that crystal orientation definitely effects the quantity of emission from shock-loaded sapphire, with the r-cut orientation making significantly less light than the a-cut and c-cut orientations at a given stress and for stresses below 470 kbar. There is a very interesting parallel in sapphire's HEL, where it has been shown that the r-cut also has a lower HEL than a-cut and c-cut (65 kbar vs > 125 kbar for a- and c-cut)[7].

This work did not demonstrate that the r-cut orientation is inherently more transparent than c-cut or a-cut at a given stress. For example, the r-cut sapphire could become optically dense and still give results consistent with the present work. Let us suppose the r-cut does indeed become optically dense. Although this would not be as desirable as perfect transparency, it would still be worth considering the use of r-cut over the c- or a-cut as an optical window for shock compression experiments. All other factors being equal, less emission from the window means less background signal to obscure the desired (sample) signal.

The r-, a-, and c-cuts used for this study are common, commercially available orientations of sapphire. They are not deliberately optimized for either emission or HEL characteristics. Based on this work and the known HEL behavior of sapphire it is plausible that, when found, the sapphire orientation with the lowest HEL will also exhibit the least amount of shock-induced emission for a given shock load.

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